The Inner 1 AU of Circumstellar Disks

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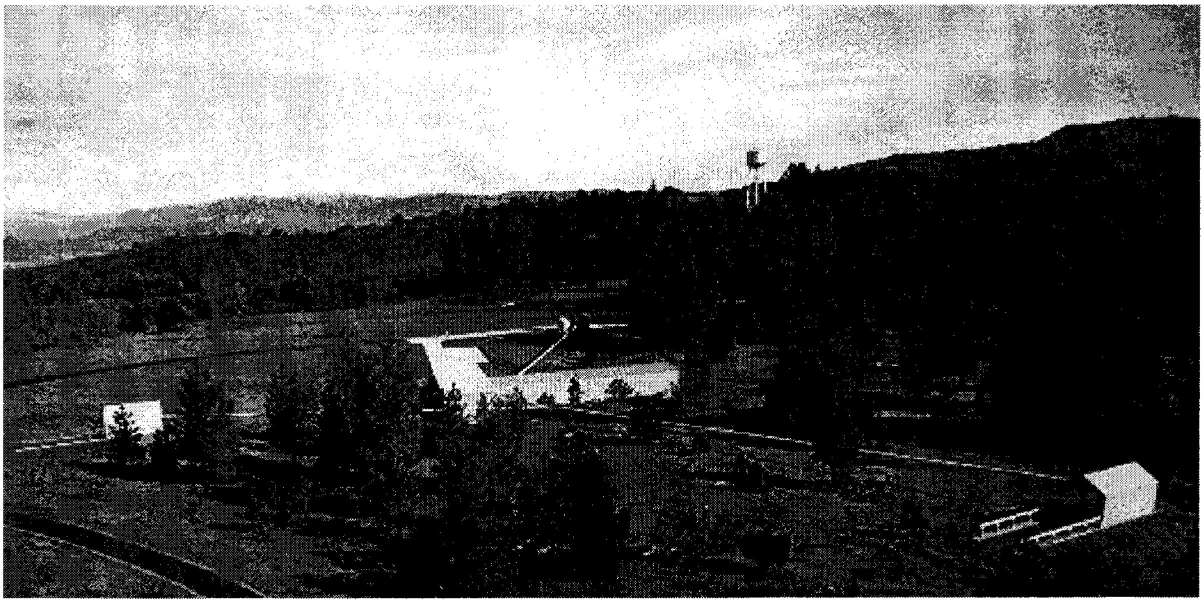
Introduction

Observational evidence for circumstellar material around most young stellar objects (YSOs) includes infrared emission in excess of the stellar photosphere, broad forbidden line profiles, and emission at millimeter wavelengths. Although the dust column density is inferred to be quite high, the sources are often optically visible, implying a geometrically flat distribution of the material. A disk morphology is also predicted by star formation theories as a consequence of conservation of angular momentum. These disks not only provide a conduit for material to accrete onto the central star, but are also a reservoir of material from which a potential planetary system might form.

The structure of YSO circumstellar disks has been studied using spectral energy distributions (SED), spectral line profiles and imaging at infrared and (sub)-millimeter wavelengths. The dust continuum emission from disks around several T Tauri sources has been resolved at millimeter wavelengths (see review by Wilner and Lay 2000). These observations are sensitive to emission from cooler dust and provide spatial information on size scales of several 10's of AU. The disk physical properties on much smaller scales ($<$ few AU) are generally inferred through examination of the spectral line shapes and modeling of the SED. One common method of describing the physical properties of the accretion disk is to parameterize the temperature (T) and surface density (Σ) as power-law functions of the radius ($T \propto r^{-q}, \Sigma \propto r^{-p}$) and the dust opacity as a power-law function of wavelength ($\kappa \propto \lambda^{\alpha}$). At 2.2 μm the disk is optically thick and the emission profile at a given radius depends on the temperature distribution (Beckwith et al 1990). Unresolved issues regarding the inner disk structure include the possible existence of inner disk holes and the validity of simple power law scalings to describe globally the temperature and density profiles of the disk. Characterizing the physical properties of the inner disk is important for theories of hydrodynamic disk winds and for understanding the initial conditions of planet formation.

Infrared interferometry provides a method to directly observe the inner disk. To date, only a few YSOs have been observed using this technique (e.g. FU Ori: Malbet et al 1998 and AB Aur: Milan-Gabet et al 1999). Here we present K-band (2.2 μm) long baseline interferometric observations of two T Tauri stars, T Tau and SU Aur. These results, along with observations of two other YSO's (MWC 147 and AB Aur) are detailed in Akeson et al 2000.

Palomar Testbed Interferometer



PTI Description	
Baselines	110m, 86m, 87m
Aperture size	40 cm
Fringe-tracking λ	2.0-2.4 μm
Spectrometer λ	1.5-2.4 μm

A detailed description of PTI can be found in Colavita et al (1999)

Data reduction

The data were obtained between September and December 1999 on the NS (110 m) baseline. The data were calibrated using the standard method described in Boden et al 1998. Briefly, a synthetic wideband channel is formed from five spectrometer channels ($\lambda = 2.0 - 2.4$). The system visibility, the visibility of an unresolved object, is measured using calibrator stars. The calibrator sizes were estimated using a blackbody fit to photometric data and were internally consistent when compared to each other (at least two calibrators were observed every night). Calibrators were chosen for their proximity to the sources and for their small angular size, minimizing systematic errors in deriving the system visibility. All calibrators used in this reduction have angular diameters < 0.8 mas and were assigned uncertainties of 0.1 mas. The data are presented in normalized squared visibility (V_2=1 for an unresolved source), which is an unbiased quantity. The uncertainties for the calibrated visibilities are a combination of the calibrator size uncertainty and the internal scatter in the data.

Models

We fit simple geometric models, uniform and Gaussian disks, to the data as size scale estimators. We also compare the data to accretion disk models from the literature.

Uniform and Gaussian profiles

For a face-on Gaussian or uniform profile, the predicted visibility is simply a function of the projected baseline. For the uniform profile, the squared visibility is

$$V^2 = \left[\frac{2J_1(\pi\theta B_p/\lambda)}{\pi\theta B_p/\lambda}\right]^2 \tag{1}$$

where J_1 is a Bessel function, θ is the diameter, and B_p is the projected baseline. For a Gaussian profile

$$V^2 = \left(\exp\left[-\frac{\pi^2}{\ln 2}\left(\frac{D}{2}\right)^2 \frac{B_p^2}{\lambda}\right]\right)^2 \tag{2}$$

where D is the FWHM.

For an inclined profile, the visibility is also a function of hour angle. As neither source shows definitive visibility structure with hour angle, we limit ourselves to the simple face-on case. Although other inclinations and position angles are not necessarily excluded by the data, we note that inclination angles near edge-on would produce significant visibility variations with hour angle, which are not seen.

Accretion disk

Emission from an accretion disk is one of the leading explanations for the infrared excess and other observed features of T Tauri stars. As we have only sampled one spatial scale in the disk, we will use accretion disk models from the literature, where the SED or millimeter imaging has been used to determine the disk parameters. As described in the introduction, these models use power-law distributions for the disk parameters.

Binary companion

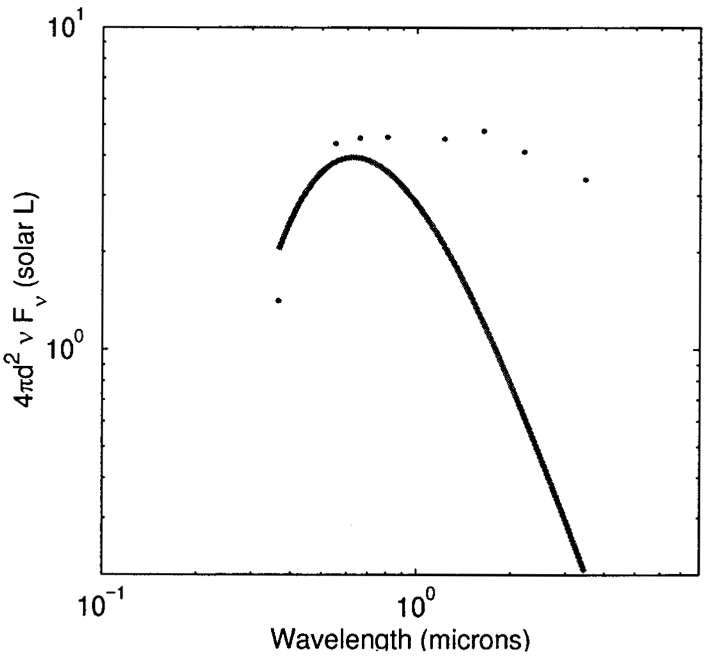
A reduction from unity visibility can be produced by a binary companion. The binary parameters which fit the data are given in Akeson et al (2000); however, no time variations in the visibilities, indicating a close orbiting companion, are seen.

T Tau

T Tauri, one of the best-studied YSOs, has an infrared companion, T Tau S, $0\overset{''}{.}7$ to the south, which is optically obscured. Both components have a near-infrared excess, suggestive of circumstellar material. Recent observations (Koresko 2000) have revealed that T Tau S is also a binary. The millimeter wave flux is dominated by material surrounding T Tau N and is consistent with circumstellar disk models with an outer radius of 40 AU (Akeson et al 1998).

At K band, T Tau N is the component with higher flux and is the source of the measured fringes (see further discussion in Akeson et al 2000). The binary separation is sufficiently large such that the fringe envelopes of the two sources do not overlap. Thus, T Tau S does not contribute any coherent flux, but does contribute incoherent flux, reducing the observed V^2 on T Tau N by $R^2/(1+R)^2$, where R is the flux ratio between T Tau N and S. For these observations the ratio has two components, the intrinsic K band flux ratio (provided by T. Beck) and an instrumental flux ratio introduced by an optical fiber.

The stellar photosphere contribution at K was estimated by fitting UBV photometry to a blackbody spectrum (figure below).



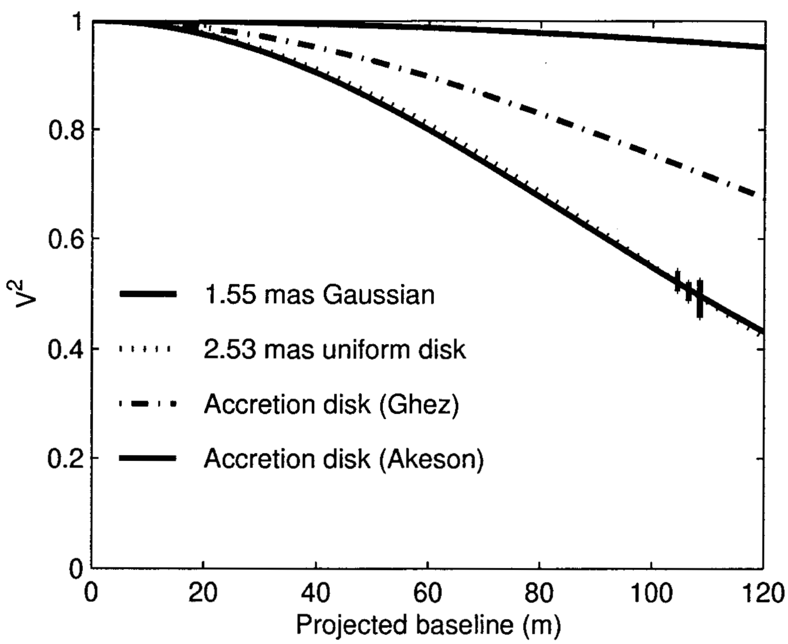
Stellar type	K1
A_V	1.39
Distance	140 pc

SED for T Tau N with stellar photosphere fit. Optical and infrared data taken from Kenyon and Hartmann (1995).

Results

The data were reduced and binned by projected baseline before being fit by Gaussian and uniform disk models. The best fit uniform disk diameter is $2.53^{+0.046}_{-0.038}$ mas (0.37 AU) and the best fit Gaussian has a FWHM of $1.55^{+0.032}_{-0.024}$ mas (0.22 AU). For the accretion disk model, we have used the parameters derived by Ghez et al (1991) with r_{inner} = 0.04 AU, r_{outer} = 100 AU, a temperature profile $T \propto r^{-0.42}$ and $T(1\ \mathrm{AU}) = 260$ K. This accretion disk model overestimates the measured visibility and, thus, underestimates the size scale of the K band emission. Using the disk parameters derived by Akeson et al (1998) from millimeter wave emission (r_{inner} = 0.01 AU, r_{outer} = 40 AU, $T \propto r^{-0.6}$, $T(1\ \mathrm{AU}) = 100$ K), the predicted size is even smaller than the Ghez model.

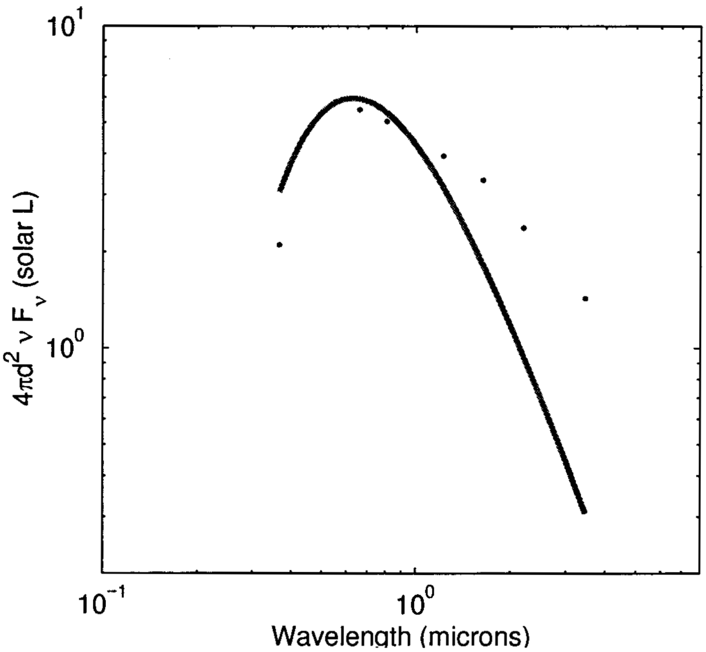
Calibrators	HD 28024
	HD 27946
Nights observed	4
# of 25 sec data points	119
Average V^2	0.29 ± 0.01[1]
Uniform disk diameter	$2.53^{+0.046}_{-0.038}$ mas
Gaussian disk (FWHM)	$1.55^{+0.032}_{-0.024}$ mas



[1]before correction for T Tau S

SU Aur

SU Aur is a T Tauri star with an SED similar to that of T Tau. Herbig and Bell (1988) designated SU Aur as the prototype of a separate classification from weak-line T Tauris due to its broad absorption lines and high luminosity ($\sim 12\ L_{\odot}$). Fitting a G2 stellar photosphere (represented by a blackbody with T_{eff}=5860) the total to stellar flux ratio at K is 2.5 (figure below).



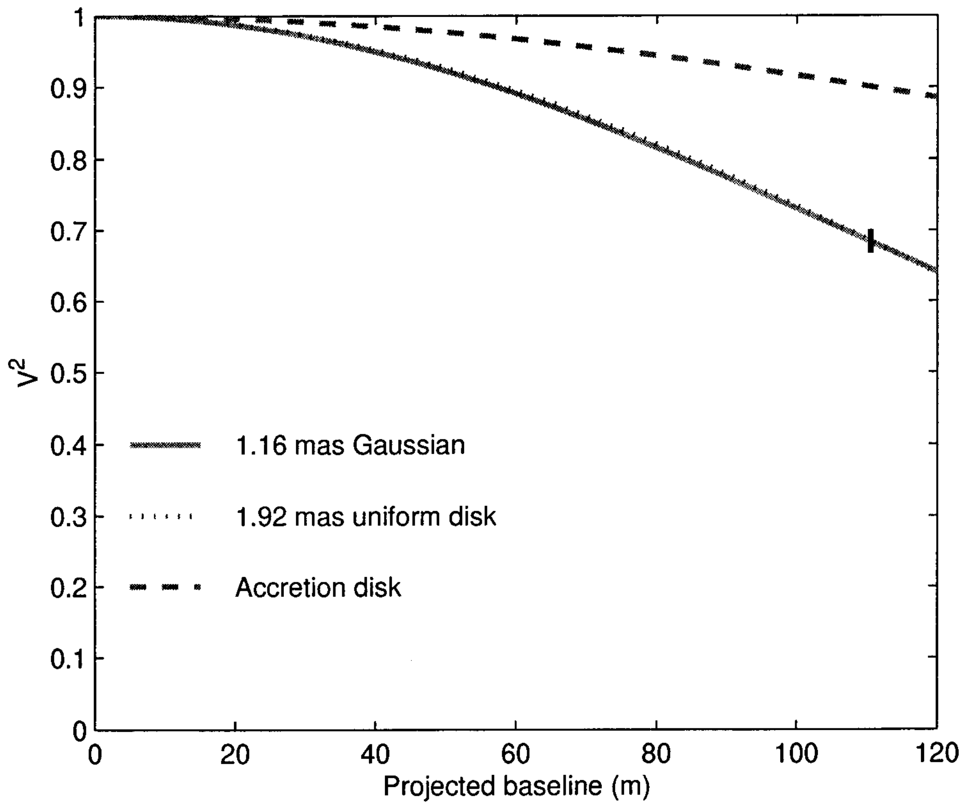
Stellar type	G2
A_V	0.9
Distance	140 pc

SED for Su Aur with stellar photosphere fit. Optical and infrared data taken from Kenyon and Hartmann (1995).

Results

The best fit diameters are $2.10^{+0.062}_{-0.074}$ mas and $1.26^{+0.053}_{-0.035}$ mas for a uniform profile and a Gaussian (FWHM) respectively. This corresponds to a physical size of 0.27 and 0.16 AU for a distance of 140 pc. The accretion disk model is taken from Beckwith et al (1990) with $r_{inner} = 0.01$ AU, $r_{outer} = 100$ AU, a temperature profile $T \propto r^{-0.51}$ and $T(1\text{ AU}) = 260$ K, where the parameters were determined by fitting 10 μm through millimeter wave fluxes. This model overestimates the observed visibility.

Calibrators	HD 28024
	HD 27946
	HD 25867
Nights observed	3
# of 25 sec data points	38
Average V^2	0.68 ± 0.02
Uniform disk diameter	$2.10^{+0.062}_{-0.074}$ mas
Gaussian disk (FWHM)	$1.26^{+0.053}_{-0.035}$ mas



Discussion

The fundamental result of these observations is that for both T Tauri sources presented here, the infrared emission arising from circumstellar material is resolved by PTI with a nominal fringe spacing of 4 mas. The measured sizes correspond to physical scales of tenths of AU. Our measured visibilities do not agree with those predicted from accretion disk models derived from near-infrared SEDs or millimeter interferometric observations. This may suggest that the single power-law relations used to describe the temperature and density structure are inadequate to reproduce both the spectral and spatial characteristics of the emission. Our data on T Tau and SU Aur require the K band emission to come from a larger region than that predicted by the accretion disk models.

Further characterization of the circumstellar material on size scales less than one AU can be achieved by extending the infrared interferometry observations presented here. During the 2000 observing season, PTI will also be operating in the NW baseline (86 m). We will be observing both sources with this second baseine to measure the visibility at shorter spacings. We will also extend the hour angle coverage and examine the data for changes in time. With data at a range of spatial scales, we can use the PTI data in conjunction with the SED and interferometric data at longer wavelengths to constrain accretion disk models parameters on size scales from 0.1 to 100 AU.

Acknowledgements

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